ASTROMETRIC AND SPACE-GEODETIC OBSERVATIONS OF POLAR WANDER

by

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Astrometric and space-geodetic observations of polar wander

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Abstract. The terrestrial location of the Earth's rotation pole has been under continuous observation since 1899 when the International Latitude Service (ILS) began conducting optical astrometric measurements of star positions to determine variations in station latitude and hence variations in the location of the rotation pole. ILS observations of polar motion continued to be made until 1979 when they were supplanted by observations taken by more accurate space-geodetic techniques. Recently, the optical astrometric measurements taken at the ILS observing stations, as well as those taken at numerous additional latitude observing stations, have been re-reduced using the final Hipparcos star catalog. This newly available optical astrometric polar motion series, which was determined using current data reduction methods and standards including the modeling of plate tectonic motions, tidal variations and ocean loading and the simultaneous estimation of nutation, and which is the longest homogeneous polar motion series currently available, allows the drift in the pole path to be newly estimated. During the 1900.0 to 1992.0 span of the smoothed Hipparcos polar motion series, the Earth's rotation pole is observed to drift at a mean rate of 3.51 ± 0.01 milliarcseconds/year (mas/yr) towards 79.2 ± 0.2 °W longitude. This new estimate for the observed trend in the pole path, which can be considered to be the present-day expression of true polar wander, is nearly the same as that given in previous studies using the homogeneous ILS polar motion series. Earth rotation

Introduction

The Earth's rotation, encompassing both the rate of rotation as well as the terrestrial location of the rotation pole, known as polar motion, is not constant but exhibits minute changes on all observable time scales ranging from subdaily to secular. This rich spectrum of observed Earth rotation changes reflects the rich variety of astronomical and geophysical phenomena that are causing the Earth's rotation to change, including, but not limited to, ocean and solid body tides, atmospheric wind and pressure changes, oceanic current and sea level height changes, torques acting at the core-mantle boundary, and post-glacial rebound.

The instrumental record of polar motion observations now spans nearly a century, during which time a drift is observed to occur in the position of the rotation pole. The trend in this observed drift of the rotation pole, which can be considered to be the present-day expression of true polar wander, is thought to be largely caused by post-glacial rebound [e.g., *Peltier and Jiang*, 1996; *Vermeersen et al.*, 1997; *Mitrovica and Milne,* 1998], although other mechanisms such as mantle convection [*Steinberger and O'Connell*, 1997] and secular changes in ice sheet mass accompanied by a secular change in sea level [e.g., *Trupin*, 1993; *James and Ivins*, 1997] should also contribute towards the observed trend in the pole path over the last century.

Observations of polar motion during the past century have been made by a variety of techniques including optical astrometry and the space-geodetic techniques of lunar and satellite laser ranging, very long baseline interferometry, and the global positioning system. Recently, the final Hipparcos star catalog has been used to re-reduce the optical astrometric measurements using current data reduction methods and standards, resulting in a newly available optical astrometric polar motion series spanning 1899.7 to 1992.0 [*Vondrák*, 1991; *Vondrák et al.*, 1992, 1995, 1997, 1998]. The availability of this new polar motion series, coupled with the importance of the observed trend in the pole path to inferences of mantle viscosity that are obtained from post-glacial rebound studies, warrants a new investigation of the observed trend in the pole path. In this study, the observed trend in the pole path is estimated from the newly available Hipparcos polar motion series, as well as from the homogeneous ILS series and from SPACE96, a polar motion series based solely upon space-geodetic measurements.

Observed Polar Motion Series

Optical Astrometric

Following the discovery of the Chandler wobble in 1891 [*Chandler*, 1891a, b], the International Latitude Service (ILS) was established by the International Association of Geodesy in 1895 for the purpose of monitoring this newly discovered motion of the Earth's rotation pole. The ILS accomplished this task by taking optical astrometric measurements of the latitude variations at six observing stations well-distributed in longitude and all located at nearly the same latitude of 39° 8' N. A seventh station, Kitab, was added in 1930 to replace the station at Tschardjui which ceased operations in 1919 due to a nearby river changing its course and adversely affecting the seeing conditions at Tschardjui. Locating all the ILS stations at nearly the same latitude allowed them to observe common star pairs by the same Horrebow-Talcott method [e.g., *Munk and MacDonald*, 1960, chap. 7], thereby allowing the polar motion to be determined from the latitude observations free of first order errors in the reference star catalog. Figure 1 shows the longitude of the ILS observing stations and the time span of the latitude observations taken at each station.

Under the auspices of the International Astronomical Union Working Group on Pole Coordinates, *Yumi and Yokoyama* [1980] re-reduced the ILS latitude observations for the express purpose of removing inconsistencies that had become evident in previous reductions of the ILS latitude observations. The *Yumi and Yokoyama* [1980] re-reduction of the ILS latitude observations utilized 772,395 latitude observations taken at the seven ILS observing stations, was based upon the IAU 1964 System of Astronomical Constants, and used the star catalog of *Melchior and Dejaiffe* [1969]. The resulting polar motion series, known as the homogeneous ILS series, spans 1899.8 to 1979.0 at 1/12-year intervals and is displayed in Figure 2 along with its low-frequency variation which was obtained by applying to the monthly mean ILS polar motion values a low-pass filter having a 6-year cutoff period. The low-pass filter employed was a simple frequency-domain boxcar filter.

During the past century, optical astrometric measurements of latitude and longitude have been taken at other stations besides those of the ILS. These other stations, although numerous and globally distributed, are in general not located at the same latitude, either with the ILS stations or with each other, and hence in general cannot observe the same star pairs. Thus, an accurate star catalog must be used in order to minimize the corrupting effects of errors in it when using these other latitude observations to determine polar motion. The Hipparcos star catalog, which includes nearly all the stars observed by the ILS and the other latitude and longitude observing stations, is just such a catalog.

The Hipparcos astrometric satellite was launched in 1989 in order to accurately measure the positions, proper motions, and parallaxes of about 100,000 stars. Commission 19 of the International Astronomical Union, recognizing the opportunity afforded by the Hipparcos satellite and the star catalog to be derived from its measurements, created a Working Group on Earth Rotation in the HIPPARCOS Reference Frame, chaired by J. Vondrák, in order to re-reduce the past optical astrometric measurements using this catalog and the current astronomical standards. *Vondrák* [1991] and *Vondrák et al.* [1992, 1995, 1997, 1998] have collected the extant optical astrometric measurements, including those taken at the ILS stations, and corrected them for instrumental effects and such systematic effects as plate tectonic motion, ocean loading, and tidal variations. The time span of the collected latitude observations, and the longitude of the stations at which these observations were taken, are shown in Figure 1. The corrected latitude, longitude, and zenith distance observations, numbering 4,315,628 from 48 instruments, have been used to solve for nutation parameters as well as for polar motion and universal time [*Vondrák*, 1991; *Vondrák et al.*, 1992, 1995, 1997, 1998]. The resulting Earth orientation series, which will be referred to here as the Hipparcos series, consists of 5-day averaged values and uncertainties for polar motion and nutation spanning 1899.7 to 1992.0, and for UT1–TAI spanning 1956.0 to 1992.0. Figure 3 displays the polar motion components of the Hipparcos series along with their low-frequency variation which was obtained by applying to the polar motion values a low-pass filter having a 6-year cutoff period. Prior to smoothing, the Hipparcos polar motion series was first linearly interpolated so that its values were equally spaced at 5-day intervals, resulting in a series of 6734 values spanning 1899.7 to 1992.0. Since the low-pass filter used to smooth the resulting equi-spaced Hipparcos polar motion series is restricted to operate on series containing only a certain number of values (6720 in the case of the Hipparcos series), the first 14 equi-spaced Hipparcos values were discarded prior to smoothing. The resulting smoothed Hipparcos polar motion series therefore spans 1900.0 to 1992.0.

Space-Geodetic

A variety of space-geodetic techniques are currently used to determine the Earth orientation parameters, including lunar and satellite laser ranging, very long baseline interferometry, and the global positioning system. However, each of these space-geodetic techniques has its own strengths and weaknesses in this regard. Not only is each technique sensitive to a different subset and/or linear combination of the Earth orientation parameters, but the averaging time for their determination is different, as is the interval between observations, their time span, and the precision with which they can be determined. By combining the individual Earth orientation series determined by each technique, a series of the Earth's orientation can be obtained that is based upon independent measurements spanning the greatest possible time interval. SPACE96 is such a combination of independent space-geodetic Earth orientation measurements [*Gross*, 1997].

Prior to their combination, each independent series of measured Earth orientation values was preprocessed in order to: (1) remove leap seconds and both solid Earth and ocean tidal terms from the universal time measurements, (2) adjust the stated uncertainties of the measurements so that the residual of each series had a reduced chi-square of one when compared to a combination of all other independent series, and (3) delete those outlying data points whose residual values were greater than three times their adjusted uncertainties [*Gross et al.*, 1998]. In addition, the bias and rate of each series was adjusted so that the series were all in alignment with each other prior to being combined together. Since each series is nominally given within the same terrestrial reference frame, the bias and rate adjustments that needed to be applied to them in order to bring them into alignment were rather small—in absolute value, the median polar motion bias adjustment was only 0.49 mas, and the median polar motion rate adjustment was only 0.11 mas/yr. A Kalman filter was then used to combine the preprocessed Earth orientation measurements. The resulting combined series, SPACE96, spans September 28.0, 1976 to February 8.0, 1997 at daily intervals and consists of values for UT1–UTC and the x- and y-components of polar motion, their formal uncertainties, and correlations. The polar motion components of SPACE96 are displayed in Figure 4 along with their low-frequency variation which was obtained by applying to the polar motion values a low-pass filter having a 6-year cutoff period.

Trend Recovery

Polar motion consists largely of: (1) the annual wobble having a nearly constant amplitude of about 100 mas, (2) the Chandler wobble having a variable amplitude ranging between about 100 and 200 mas, (3) quasi-periodic variations on decadal time scales having an amplitude of about 30 mas, and (4) a trend, the estimation of which is the subject of this study. The design problem to be solved in estimating the trend is to devise a scheme that will yield an unbiased result for its rate and direction given that the trend exists in the presence of the above large-amplitude periodic and quasi-periodic variations. Various approaches have been taken in the past to account for the presence of the annual, Chandler, and decadal wobbles when estimating the trend. The annual wobble has been removed in the past by both a least-squares fit [*Wilson and Gabay*, 1981; *Gross*, 1982; *McCarthy and Luzum*, 1996], and by a seasonal adjustment of the polar motion series [*Wilson and Vicente*, 1980]. The Chandler wobble has been removed in the past by both a least-squares fit for periodic terms [*Dickman*, 1981; *McCarthy and Luzum*, 1996], and by deconvolution [*Wilson and Vicente*, 1980; *Wilson and Gabay*, 1981]. Smoothing has also been used in the past to remove the annual and Chandler wobbles [*Okamoto and Kikuchi*, 1983]. The decadal-scale variations have been removed in the past by modeling them as being strictly periodic at a single frequency of 1/31 cpy and then least-squares fitting a sinusoid at this single frequency [*Dickman*, 1981; *McCarthy and Luzum*, 1996].

In this study, the annual and Chandler wobbles have been removed by applying to the polar motion series a low-pass filter having a 6-year cutoff period. The trend is then recovered from the low-pass filtered series, which are displayed in Figure 5, by a simultaneous weighted least-squares fit for a mean, trend, and periodic terms at all the frequencies of the spectral peaks evident in the amplitude spectrum of the smoothed polar motion series. This amplitude spectrum of the smoothed polar motion series was not obtained by Fourier analysis, but was instead obtained by simultaneously fitting a mean, trend, and one periodic term to the smoothed observations. The fit was repeated many different times as the period of the periodic term was systematically varied between 6 years and a period equal to the length of the smoothed series at intervals of 0.01 years. Plotting the amplitude of the periodic term as a function of prograde and retrograde frequency yielded the amplitude spectrum of the smoothed polar motion series. The frequencies of the peaks in this amplitude spectrum were the frequencies subsequently used in the simultaneous weighted least-squares fit for the mean, trend, and periodic terms at all these frequencies. Since the time span of each of the three polar motion series studied here is different, the number of the periodic terms included in the least-squares fit is different for each series. For the smoothed ILS series, 12 such periodic terms were included in the least-squares fit; for the smoothed Hipparcos series, 14 such periodic terms were included in the fit; and for the smoothed SPACE96 series, 3 such periodic terms were included. The resulting model obtained by this simultaneous weighted least-squares fit for a mean, trend, and all periodic terms is shown in Figure 5 as the dashed lines. As can be seen, this model is a reasonably good fit to the data, with the discrepancy being most evident in the x-component. Treating polar motion as a complex-valued quantity, the root-mean-square (rms) of the misfit between the recovered model and the observations is only 2.9 mas for the ILS series, 1.5 mas for the Hipparcos series, and 1.4 mas for the SPACE96 series. By simultaneously solving for periodic terms at all the frequencies of the peaks evident in the spectrum of the smoothed polar motion series, the quasi-periodic nature of the decadal variations is taken into account. The resulting estimate for the trend should thus be unbiased, not only by the presence of the annual and Chandler wobbles since they have been removed by smoothing, but also by the quasi-periodic decadal variations.

The estimates for the rate and direction of the trends recovered by the above method are given in Table 1 along with other recent trend estimates. Using the homogenous ILS polar motion series, *Dickman* [1981] obtained a trend of 3.521 ± 0.094 mas/yr towards 80.1 ± 1.6 °W longitude. In this study, applying the above method to the same ILS series yields a trend of 3.81 ± 0.07 mas/yr towards 75.5 ± 1.0 °W, which differs from that obtained by *Dickman* [1981] by only 4.6° in direction and 8.2% in rate. Using the Hipparcos polar motion series based upon the final Hipparcos star catalog, *Vondrák et al.* [1998] obtained a trend of 3.39 mas/yr in a direction towards 78.5 °W longitude. In this study, applying the above method to the same Hipparcos polar motion series yields a trend of 3.51 ± 0.01 mas/yr towards 79.2 ± 0.20 °W, which differs from that obtained by *Vondrák et al.* [1998] by only 0.7° in direction and 3.5% in rate. The trend estimates obtained using space-geodetic measurements, those obtained here using SPACE96 and those of *McCarthy and Luzum* [1996] using the NEOS series, should not be directly compared with each other since the time span of these two series are different. This differing time span is particularly problematic given that the space-geodetic measurements span only about 20 years (see the following section).

Preferred Trend Estimate

The trend in the pole path has been estimated here using three different polar motion series: (1) the smoothed homogeneous ILS series spanning 79.2 years from 1899.8 to 1979.0, (2) the smoothed Hipparcos series spanning 92.0 years from 1900.0 to 1992.0, and (3) the smoothed SPACE96 series spanning 20.4 years from 1976.7 to 1997.1. Because of the presence of the quasi-periodic decadal variations in the pole path, it is desirable to estimate the trend from polar motion measurements having the greatest possible time span. Even though space-geodetic measurements of polar motion are more accurate than astrometric measurements, since the time span of the space-geodetic series used here is relatively short, being only 20.4 years, the trend estimated from it is likely to be unreliable due to the corrupting influence of decadal-scale polar motion variations having periods greater than the span of the measurements. More reliable estimates for the trend in the pole path are likely to be obtained using the astrometric series since their time span is much greater than that of the space-geodetic series. Of the two astrometric series studied here, the Hipparcos series spans the greater length of time, is based upon a much greater number of latitude observations, and was determined using current data reduction methods and standards including the modeling of plate tectonic motions, tidal variations and ocean loading and the simultaneous determination of nutation. Thus, of the series studied here, the most reliable estimate for the trend in the pole path is likely to be that obtained using the Hipparcos polar motion series. The preferred trend estimate is therefore 3.51 ± 0.01 mas/yr towards 79.2 ± 0.20 °W longitude.

Discussion

The uncertainties given above and in Table 1 for the trend estimates determined here are the formal uncertainties obtained during the weighted least-squares fit for the trend. Because of possible systematic effects due, for example, to the presence of decadal- and perhaps century-scale polar motion variations having periods greater than the span of the measurements, the true error in the trend estimates is likely to be greater than the quoted formal uncertainties.

It is encouraging that the trend estimated from the accurate space-geodetic measurements is in reasonably close agreement with those estimated from the less accurate optical astrometric measurements. The trend estimated from the SPACE96 series differs from the preferred trend estimated from the Hipparcos series by only 5.3° in direction and 17.5% in rate. This is remarkable agreement given the relative shortness of the time span of the space-geodetic measurements, and is confirmation that the trend observed in the astrometric series is not an artifact of the astrometric measurement technique or data reduction method.

As seen in Figure 5, the smoothed Hipparcos and ILS polar motion series agree reasonably well with each other—the correlation coefficient between their detrended x-components is 0.78 and that between their detrended y-components is 0.71, with a 95% significance level for the correlation coefficient of 0.48 for the x-component and 0.58 for the y-component. However, there is little agreement evident between the smoothed Hipparcos and SPACE96 polar motion series. These two series overlap during 1976.7 to 1992.0 and during this time span the Hipparcos series exhibits decadal-scale variations of greater amplitude than those exhibited by the SPACE96 series. This discrepancy between the less accurately determined optical astrometric Hipparcos series and the more accurately determined space-geodetic SPACE96 series raises concerns about the reality of the decadal-scale variations exhibited by the Hipparcos series, at least since 1976.7. An investigation of this discrepancy is beyond the scope of the present paper. However, it should be noted that because of the trend estimation procedure adopted here, the values obtained here for the trend rate and direction are unbiased by the presence of the quasi-periodic decadal-scale polar motion variations, whether real or artifact.

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Figure 1. The longitudes of the latitude observing stations whose measurements were used to generate the Hipparcos polar motion series [*Vondrák*, 1991; *Vondrák et al.*, 1992, 1995, 1997, 1998], and the time span of the measurements taken at each station. The ILS observing stations, whose observations were used to generate the homogeneous ILS polar motion series [*Yumi and Yokoyama*, 1980], are denoted here by UK for Ukiah, CI for Cincinnati, GT for Gaithersburg, CA for Carloforte, TS for Tschardjui, KZ for Kitab, and MZ for Mizusawa.

Figure 2. The x-component (top panel) and y-component (bottom panel) of the homogeneous ILS polar motion series (black curve). By convention, the x-component is positive towards the Greenwich meridian and the y-component is positive towards 90°W longitude. The observed variation in amplitude on an approximate 6-year time period results from the beating between the annual wobble, which has a 12-month period, and the Chandler wobble, which has a 14-month period. The red curve, obtained by smoothing the polar motion series by applying a low-pass filter having a 6-year cutoff period, shows quasi-periodic polar motion variations on decadal time scales.

Figure 3. As in Figure 2 but for the Hipparcos polar motion series.

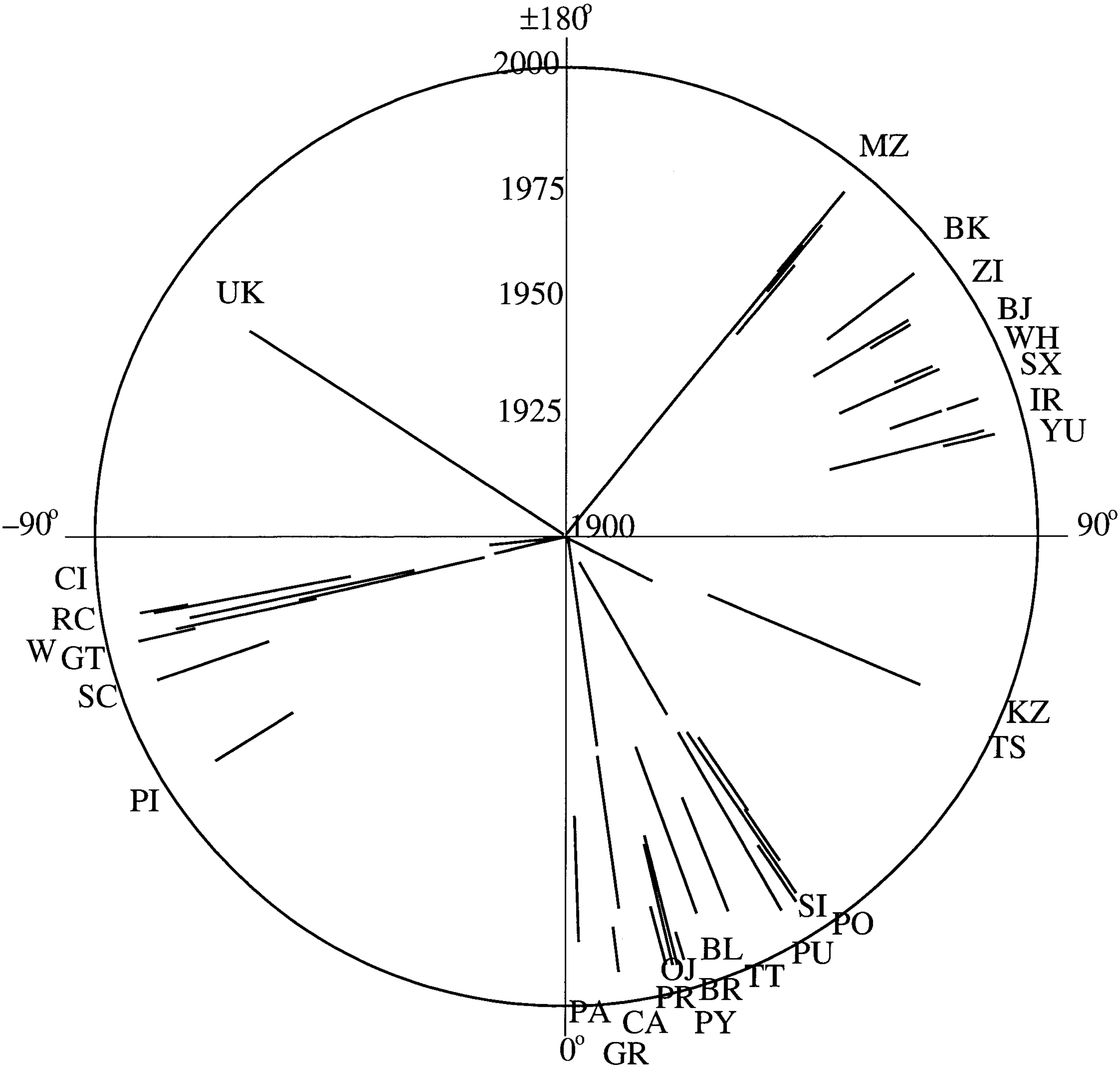
Figure 4. As in Figure 2 but for the SPACE96 polar motion series.

Figure 5. The x-component (top panel) and y-component (bottom panel) of the smoothed ILS (solid green curve), Hipparcos (solid blue curve), and SPACE96 (solid red curve) polar motion series that have been reproduced from Figures 2, 3, and 4, respectively. For clarity, the x- and y-components of the smoothed ILS series have been shifted up by 100 mas, and the x- and y-components of the smoothed SPACE96 series have been shifted down by 100 mas. The dashed lines, most evident in the x-components, indicate the models recovered by simultaneously fitting a mean, trend, and periodic terms at all the frequencies of the spectral peaks evident in the amplitude spectrum of the respective series. The dotted lines indicate the trends in the respective smoothed polar motion series thus estimated.

Table 1. Recent Estimates of the Trend in the Pole Path from Astrometric and Space-Geodetic Measurements

Data Set	Data Span	Estimated Trend Rate (mas/yr)	Estimated Trend Direction (degrees W)
Hipparcos Polar Motion Series			
Quasi-FK5 catalog; *Vondrák et al.* [1995]	1899.7–1991.0	3.31	78.15
Prelim. Hip. cat.; *Vondrák et al.* [1997]	1899.7–1992.0	3.70	78.14
Final Hip. cat.; *Vondrák et al.* [1998]	1899.7–1992.0	3.39	78.5
Final Hip. cat.; This study (preferred est.)	1900.0–1992.0	3.51 ± 0.01	79.2 ± 0.2
ILS Polar Motion Series			
Wilson and Vicente [1980]	1900–1977	3.4	78
Dickman [1981]	1899.8–1979.0	3.521 ± 0.094	80.1 ± 1.6
Chao [1983]	1899.8–1979.0	3.52	79.4
Okamoto and Kikuchi [1983]	1899.0–1979.0	3.456	80.56
This study	1899.8–1979.0	3.81 ± 0.07	75.5 ± 1.0
ILS Polar Motion Excitation Series			
Wilson and Vicente [1980]	1900–1977	3.4	66
Wilson and Gabay [1981]	1901–1970	3.3	65
Other Astrometric Polar Motion (PM) Series			
PM fit to ILS latitude obs.; *Gross* [1982]	1899.7–1979.0	3.91	69.9
Latitude Observations			
9 latitude stations; *Zhao and Dong* [1988]	1900–1978	3.62	89
M+K+C+G+U*; *Zhao and Dong* [1988]	1900–1978	3.51	79
M+K+C+G+U*; *Vondrák* [1994]	1899.8–1979.0	3.24	84.9
M+K+C+G*; *Vondrák* [1994]	1899.8–1979.0	2.97	77.7
Space-Geodetic Polar Motion Series			
NEOS; *McCarthy and Luzum* [1996]	1976.0–1994	3.39 ± 0.53	85.4 ± 4.0
SPACE96; This study	1976.7–1997.1	4.123 ± 0.002	73.9 ± 0.03
Combined Astrometric and Space-Geodetic Series			
Vondrák [1985]	1900.0–1984.0	3.29	78.2
McCarthy and Luzum [1996]	1899.8–1994	3.33 ± 0.08	75.0 ± 1.1

*M, Mizusawa; K, Kitab; C, Carloforte; G, Gaithersburg; U, Ukiah


±180°
2000
1975
1950
1925
1900
−90°
90°
0°
MZ
BK
ZI
BJ
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SX
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Fig. 1

ILS POLAR MOTION SERIES

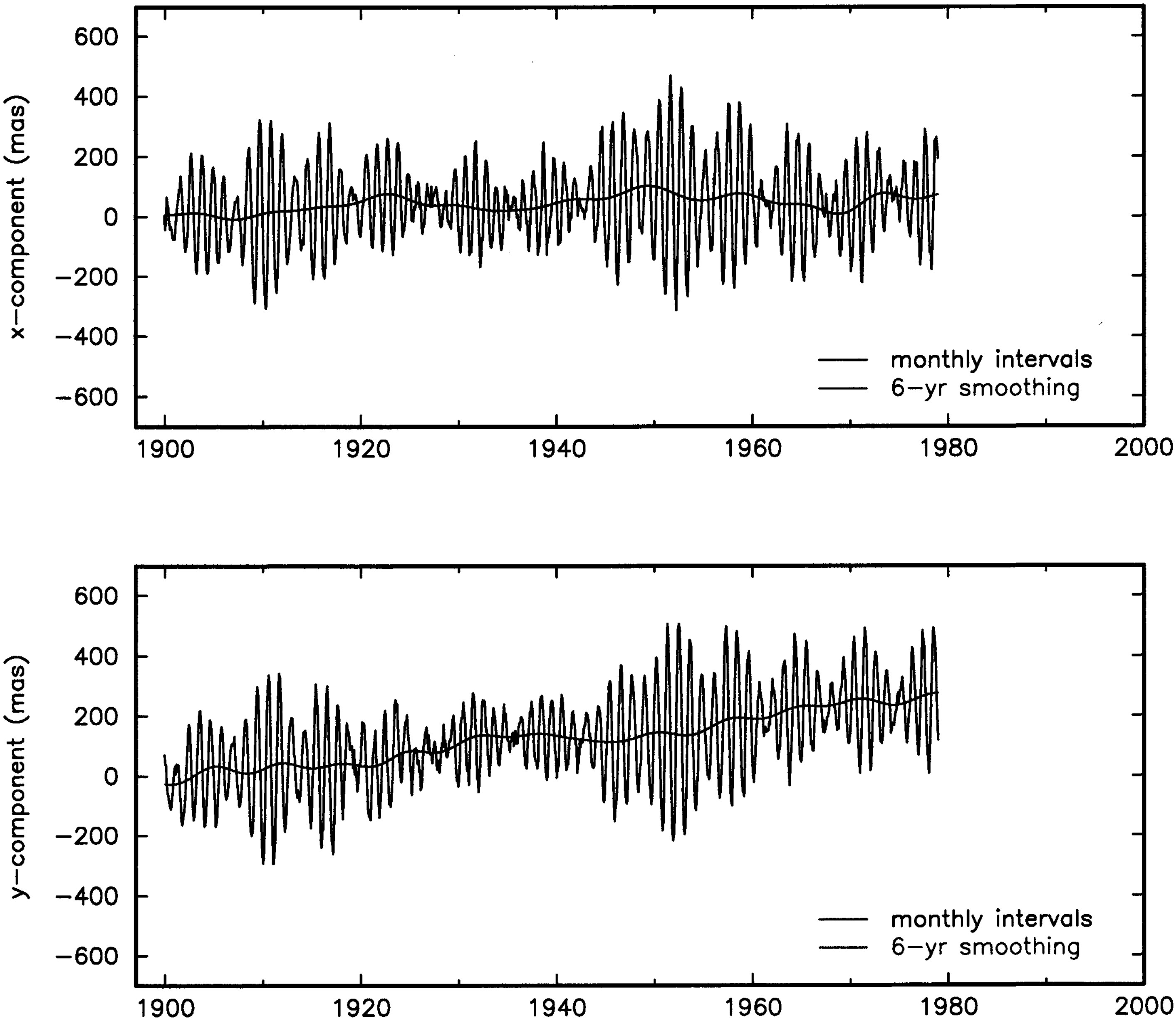

Fig. 2

HIPPARCOS POLAR MOTION SERIES

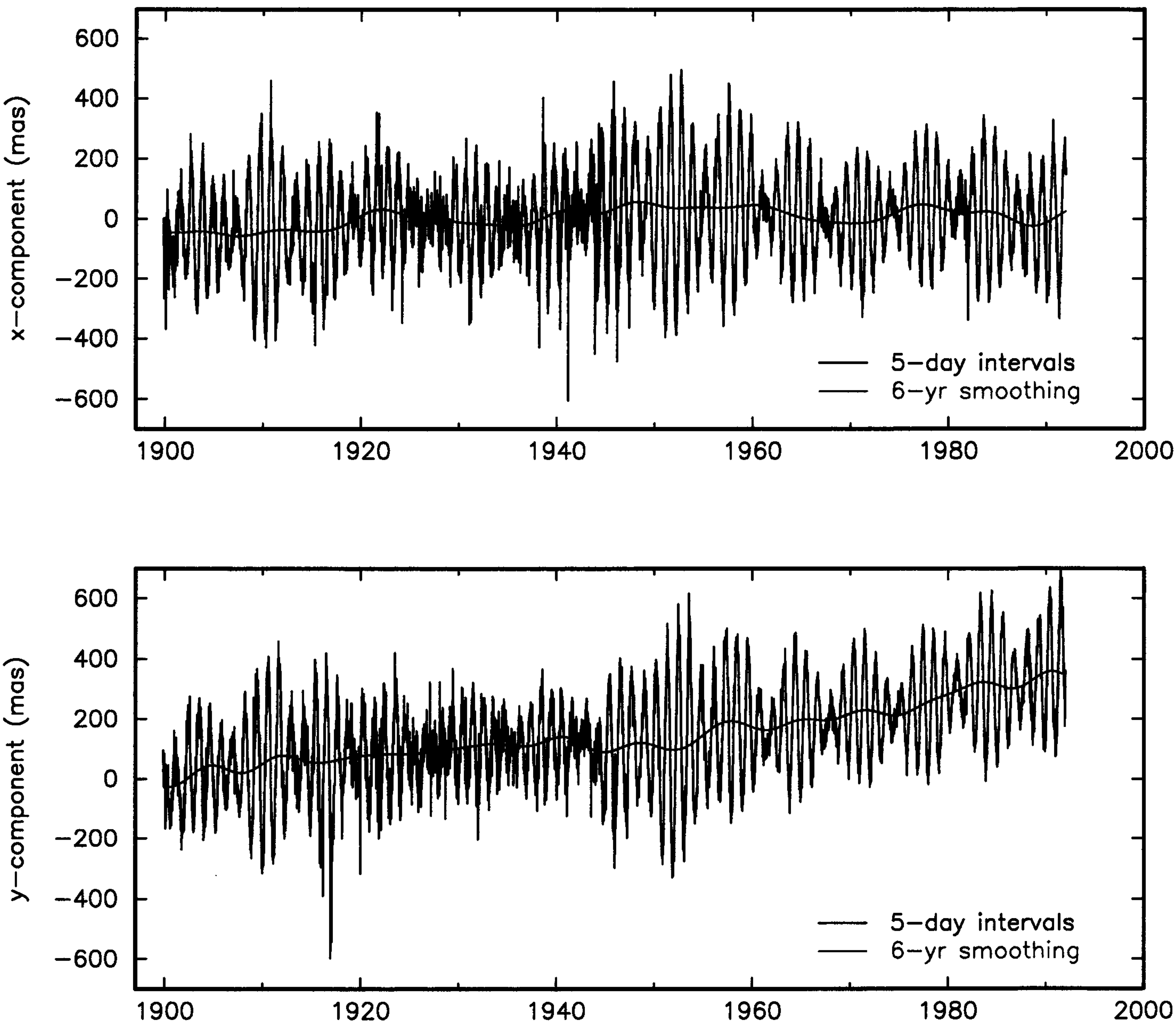

Fig. 3

SPACE96 POLAR MOTION SERIES

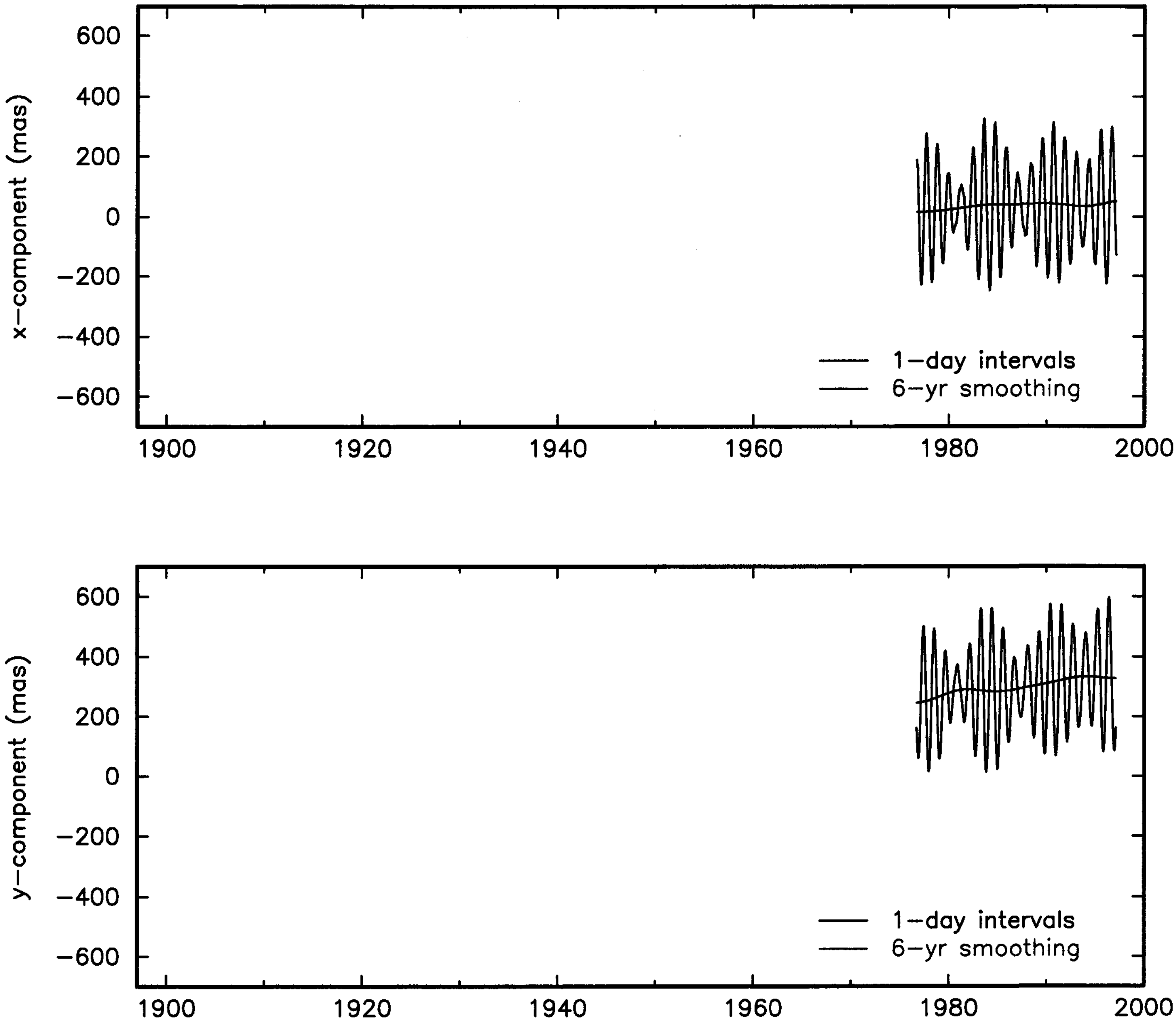

Fig. 4

SMOOTHED POLAR MOTION SERIES

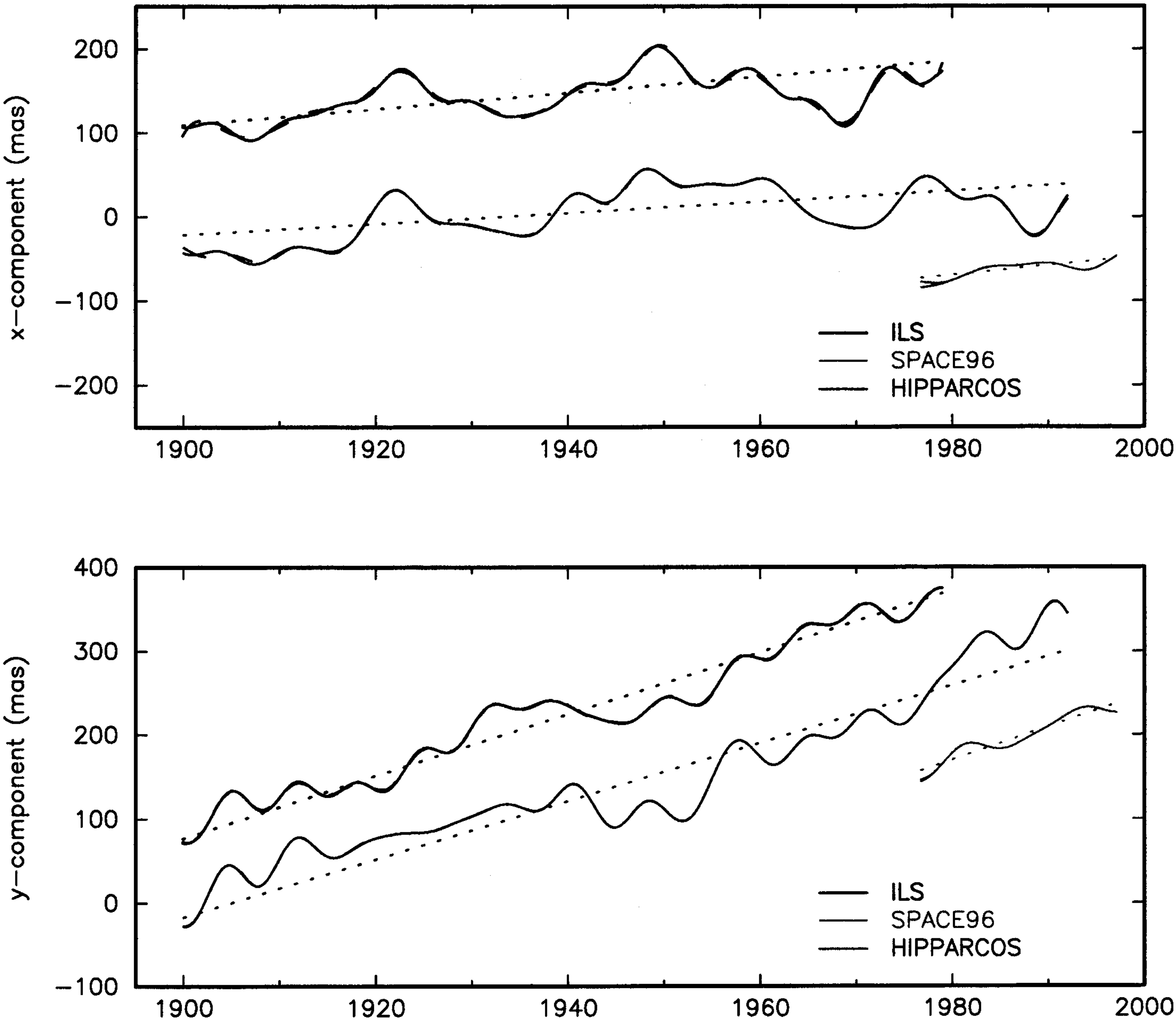

Fig. 5